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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

TRANSFORMATION OF WAVES ACROSS THE SURF ZONE

by

Galo Padilla Teran

March 1981

Thesis Advisor: E.B. Thornton

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The range of breaking, and the coefficients used in the breaking criteria by Goda, are modified in order to obtain a model which better fits the distribution of observed hieghts, and which matches the model and observed rms wave heights. The results are quite good, with error envelope for predicted rms wave heights less than 20%. Linear shoaling theory is applied to the model and found to be as good as applying nonlinear theory.

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Transformation of Waves Across the Surf Zone

by

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ABSTRACT

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LIST OF SYMBOLS

$\bar{a}$	Root-mean-square (rms) amplitude
A	Goda's breaking criteria coefficient
C_g	Speed of energy propagation
E	Energy density
g	Acceleration due to gravity
h	Local depth below still water level
ζ	Sea surface elevation
H_b	Breaking wave height
H_o	Deep water wave height
$\hat{H}$	Wave height parameterizing truncated Rayleigh distribution
H_{rms}	Root mean square wave height
H_{KE}	Transfer function that relates the velocity spectrum components to the kinetic energy
H_s	Transfer function that relates potential energy to the kinetic energy
k	Wave number
K	Goda's breaking criteria coefficient
KE	Kinetic energy
K_s	Shoaling coefficient
L_o	Deep water wave length
m_o	Lowest moment variance of the frequency spectrum
p	Probability density function of wave heights
p_r	Probability density function of unbroken waves
S_u	Horizontal velocity spectrum, x-component
S_v	Horizontal velocity spectrum, y-component

T	Wave period
X	Ratio wave height to deep water wave height
X_1	Higher limit of breaking range
X_2	Lower limit of breaking range
z_m	Measurement elevation
α_0	Deep water incident angle
α_b	Incident wave angle at breaking
β	Bottom slope
δ	Delta function
γ	Ratio of breaking wave height to depth of water at breaking
ν	Root mean square spread of the noise about the mean frequency
ρ	Water density

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I. INTRODUCTION

The evaluation of an irregular group of shoaling waves as they approach and pass through the breaker zone is a complex process which requires special measurements and analysis considerations. The usual approach to shallow water wave transformations is to predict, from a single "representative" set of deep water parameters, the wave height, the wavelength and the frequency at specific shallow water depths, using linear shoaling theory. The primary objection to this approach is that a single set of deep water wave parameters does not realistically represent the distributional characteristics of naturally occurring sea surface waves. A secondary objection arises from the use of linear transformations which become inadequate when applied through the surf zone (Wood, 1974).

Wave heights in deep water, having Gaussian surface elevations, are described by the Rayleigh distribution (Longuet-Higgins, 1952). Waves propagating toward shore can increase in height due to shoaling effects, refraction and wave interactions, and eventually reach a depth where they start breaking. The energy dissipation due to breaking has been simulated (Goda, 1975) by truncating the tail of the Rayleigh distribution.

Experiments were conducted at Torrey Pines Beach, San Diego, California, during November 1978. Sea surface elevations, pressures and velocities were measured at closely spaced locations in a line extending from 10m depth to inside the surf zone. This thesis applies Goda's model to the measurements in order to examine the shoaling and transformation of wave heights and their probability density functions (pdf's) from deep water to breaking and across the surf zone to the shoreline.

II. THEORETICAL BACKGROUND

A. RAYLEIGH DISTRIBUTION

The Rayleigh distribution was shown theoretically by Longuet-Higgins (1952) to apply to deep water wave heights on the assumption that the sea waves are a narrow-banded Gaussian process. Barber (1950) had earlier presented empirical evidence that the Rayleigh distribution agreed with the measured distribution of waves. On the assumption that the wave height is twice the wave amplitude, the wave height probability density is then represented by

$$p(H) = 2H/\overline{H}_{rms}^2 \exp(-H^2/\overline{H}_{rms}^2) \tag{1}$$

where $\overline{H}_{rms}$ is the rms wave height.

Using pressure records in the Gulf of Mexico, Longuet-Higgins (1975) observed that the Rayleigh distribution fits the observed distribution reasonably well in "fairly deep water". He found that there is a slight excess of waves with heights near the middle of the range and a deficit at the two extremes. Since much of the high-frequency portions of the wave records were filtered out by the pressure transducer, Longuet-Higgins (1975) suggested that the narrow band approximation may not be as applicable for the unfiltered records. In shallow water with much steeper waves, the Rayleigh distribution can again be expected to be less applicable due to the non-linearities.

Since the Rayleigh distribution theoretically did not apply to broadband wave spectra, Goda (1970) numerically simulated wave profiles, where the amplitudes were specified by various theoretical spectra of varying bandwidth and the phase was random. He then examined the simulated records for surface elevations, crest-to-trough wave heights and zero-up-crossing wave heights. He found that, using the zero-up-crossing determination of wave heights, the Rayleigh distribution is a good approximation irrespective of the spectral bandwidth. Tayfun (1977), in studying the transformation of deep water waves to shallow water waves, showed that the Rayleigh distribution for wave amplitude was generally applicable to all bandwidths.

The Rayleigh distribution is applied correctly only to low waves in deep water (Longuet-Higgins, 1975), since it is assumed that the contributions from different parts of the generating area are linearly superposable. Under this assumption, the distribution clearly should not hold for waves approaching maximum height, i.e., close to breaking, as in the surf region or even in the open sea with whitecaps. It has been found by several authors (Chakrabarti and Cooley, 1977; Forristal, 1978) that the theoretical Rayleigh distribution over-predicts the maximum wave in the tail compared with large wave observations. Forristal (1978) attributed the differences to the non-linear, non-Gaussian and skewed nature of the free surface.

Tayfun (1980) examined non-linear effects by considering an amplitude-modulated Stokian wave process with the restriction that the underlaying first order spectrum is narrow band. The surface displacements were found to be non-Gaussian and skewed, and wave heights distributed according to the Rayleigh probability law, particularly for low and medium wave height ranges. On the basis of the results obtained, Tayfun (1980) concludes that the non-Gaussian characteristics of the free surface do not directly result in reducing maximum wave heights in a manner consistent with field observations and that a more plausible mechanism is wave breaking, which is a non-linear effect not directly accounted for in the analytical wave models currently available.

Longuet-Higgins (1980) analyzed the effects of non-linearity and finite bandwidth on the distribution of wave heights to explain the differences with observations found by Forristal. He found that the reason for the discrepancy could be accounted for by the presence of free background "noise" in the spectrum, outside the dominant peak, and that it was not due to a finite-amplitude effect. Longuet-Higgins concludes that the distribution of wave heights even in a storm is well described by the Rayleigh distribution, provided the rms amplitude, $\bar{a}$, is estimated from the original record and not from the frequency spectrum as $\bar{a} = (2m_0)^{1/2}$. The effect of finite bandwidth is estimated from a model assuming low background noise linearly superposed on a very narrow (delta function) spectrum. For narrow bandwidths, he obtains the formula

$$\bar{a}^2/2m_0 = 1 - 0.734\ \nu^2 \tag{2}$$

where ν is the rms spread of the noise about the mean frequency. Values of ν^2 corresponding to Pierson-Moskowitz (broad-band) spectra also give results in close agreement with observation. Therefore, the Rayleigh distributions calculated in this paper are parameterized using the rms wave height.

B. TRUNCATED PROBABILITY DISTRIBUTIONS

In concept, waves are described by the joint distribution of height, period (or equivalent wavelength) and direction. To simplify the analysis, all authors assume a very narrow band frequency spectrum and a narrow directional spectrum, so that all the wave heights of the distribution are associated with a single mean frequency and mean direction. Therefore, starting in deep water, the waves are described by the unaltered single-parameter Rayleigh distribution, with the implied assumptions. The deep water wave heights are transformed into shallow water waves using shoaling theory in which frictional dissipation is neglected. Eventually the waves reach such shallow water that they start to break, with the largest waves breaking furthest offshore first. Wave breaking is simulated by truncating the tail of the Rayleigh distribution.

1. Collins Distribution

Collins (1970) was the first to apply the technique of a truncated distribution to describe the effects of wave breaking, using a sharp cut-off with all broken waves equal to H_b which results in a delta function at H_b. Collins does not give an explicit formula for his distribution, but it would be the same as the described by Battjes (1974) (see below). He used linear shoaling theory and the breaking criterion after Le Mehauté and Koh (1967

$$H_b/H_0 = 0.76 \tan^{1/7}\beta(H_0/L_0)^{-1/4} \tag{3}$$

where tan β is the bottom slope and H_0 and L_0 are the deep water wave height and length, respectively. For waves breaking at an angle α, the bottom slope is actually $\tan \beta \cos \alpha_b$, and H_0 should be replaced by $H_0 \cos^{1/2} \alpha_0$. The various distributions, and how they are truncated are showed schematically in Table I.

2. Battjes Distribution

Battjes (1974, 1978) again used a sharp cut-off of waves and applied the breaking criterion based on Miche's formula for the maximum height of periodic waves of constant form,

$$H_b \simeq 0.88/k \tanh (\gamma/0.88\ kh) \tag{4}$$

where γ is an adjustable coefficient. In shallow water (4) reduces to

$$H_b = \gamma h . \tag{5}$$

He uses linear theory to shoal the waves. The probability density for breaking wave heights is given by:

$$p(H) = H/2\hat{H}^2 \exp[-1/2(H^2/\hat{H}^2)], \quad \text{for } 0 \le H \le H_b \tag{6}$$

$$p(H) = \exp[-1/2(H_b^2/\hat{H}^2)]\,\delta(H - H_b), \quad \text{for} \quad H > H_b \tag{7}$$

where $\hat{H}$ is the wave height parameterizing the truncated Rayleigh distribution by Battjes. All waves that have broken, or are breaking, assume the height prescribed by (7); this results in a delta function at the truncation height, H_b, of the distribution (see Table I).

3. Kuo and Kuo Distribution

Kuo and Kuo (1974) investigated the effect of breaking on wave statistics using a conditional Rayleigh distribution sharply truncated, specified by the breaking wave height simply proportional to local water depth, equation (5). The conditional probability density function of wave heights, $p_b(H)$, is calculated using the following equation,

$$p_b(H) = p(H/0 \le H \le H_b) = \frac{p(H)}{\int_0^{H_b} p(H)\,dH}, \quad \text{for } 0 \le H \le H_b \tag{8}$$

$$= 0 \quad , \quad \text{for } H > H_b .$$

Describing the conditional probability in this manner results in the proportional redistribution of probability density associated with the broken or breaking waves over the range of H. This removes the delta function at the breaking wave height, H_b, previously described by Collins and Battjes. Table I shows the original Rayleigh distribution with dotted lines, and the modified Rayleigh distributions in heavy lines after applying the cut-off to the tails using the breaking criterion. The distribution by Kuo and Kuo is more realistic but still results in a sharp cut-off of the distribution at the breaking heights.

5. Goda Distribution

Goda (1975) derived a more realistically truncated distribution, qualitatively anyway, by requiring a gradual cut-off of the distribution. He uses a shoaled Rayleigh distribution to describe the unbroken wave heights at shoreward locations prior to applying his cut-off which is given by

$$p_o(H) = 4H/K_s^2H_o^2 \exp(-2H^2/K_s^2H_o^2) \qquad (9)$$

where K_s is the shoaling coefficient. Goda (1975) calculated the wave shoaling using the nonlinear theory of Shuto (1974): which dictates the following:

$$0 < gHT^2/h^2 \leq 30: \text{ Small Amplitude Theory} \qquad (10)$$

$$30 < gHT^2/h^2 \leq 50: \quad H\,h^{2/7} = \text{constant} \qquad (11)$$

$$50 < gHT^2/h^2 \leq \infty: \quad Hh^{5/2}[\sqrt{gHT^2/h^2} - 2\sqrt{3}] = \text{constant.} \tag{12}$$

Goda assumes that wave breaking occurs in a range of wave heights between H_2 and H_1, with varying probability. The probability density function of unbroken waves only is expressed as:

$$p_r(X) = p_o(X) \quad ; \quad \text{for } X \leq X_2 \tag{13}$$

$$p_r(X) = p_o(X) - \frac{X - X_2}{X_1 - X_2} p_o(X_1); \quad \text{for } X_2 < X \leq X_1 \tag{13}$$

$$p_r(X) = 0 \quad ; \quad \text{for } X_1 < X \tag{15}$$

where, normalized wave heights are defined by $X = H/H_o$, $X_1 = H_1/H_o$ and $X_2 = H_2/H_o$. The artifice of spreading breakers over a range partly represents the inherent variability of breaker heights, and partly compensates for the simplification of using a single wave period in the estimation of breaker height. Broken waves generally have some height smaller than X_1. Since no theory is available for describing waves after they have broken, the heights of broken waves are assumed to be redistributed across the range and to be proportional to the unbroken waves as was done by Kuo and Kuo (1975). Therefore, the conditional probability density function for all heights is calculated by

$$p(X) = \frac{p_r(X)}{\int_0^{X_1} p_r(X)\,dx} \tag{16}$$

where:

$$\int_0^{X_1} p_r(X)dX = 1 - \{1 + \alpha^2 X_{.}(X_1 - X_2)\}e^{-\alpha^2 X_1^2}, \tag{17}$$

is a constant of proportionality applied to $p_r(X)$ to normalize the pdf. In equation (17), the constant, α, is equal to $\sqrt{2}/K_s$.

The breaker height is estimated using the following formula, which is an approximate expression for Goda's breaker index (1970) based on laboratory data,

$$\frac{H_b}{H_o} = A\,\frac{L_o}{H_o}\{1 - \exp[-1.5\,\frac{\pi h}{H_o}\,\frac{H_o}{L_o}(1 + K\,\tan^p\beta)]\}\ , \tag{18}$$

where tan β denotes the bottom slope and the coefficients are assigned the following values for best-fitting to the index curves,

$$A = 0.17, \quad K = 15, \quad \text{and} \quad p = 4/3.$$

The range of breaker height, $X_1 - X_2$, is calculated by assigning the following values for A:

$$A_1 = 0.18 \quad \text{for} \quad X_1,$$

$$A_2 = \frac{2}{3}A_1 = 0.12 \quad \text{for} \quad X_2.$$

The upper limit of A_1 was selected by considering the variability of breaker heights, whereas the lower limit of A_2 was chosen simply as two-thirds of A_1. The coefficients used are based on matching laboratory data taken on a 1/10 and 1/50 beach slope and several field experiments. The Goda model is applied here to the experimental data described below.

5. Summary

The common idea of these studies is to cut-off the portion of wave height distribution beyond the breaker height, which is controlled by the water depth and other factors. The methods differ in the techniques of cut-off and the formulae used to define breaker heights.

III. EXPERIMENT

Experiments were conducted at Torrey Pines Beach, San Diego, California, during November 1978, as part of the Nearshore Sediment Transport Study. At this site there is a gentle sloping, moderately sorted, fine-grained sandy beach. The beach profile shows no well-developed bar structure and is remarkably free from longshore topographic inhomogeneities. Winds during the experiments were light, and variable in direction. Shadowing by offshore islands and offshore refraction, limits the angles of wave incidence in 10m depth to less than 15°. During the experiments, significant offshore wave heights varied between 60 and 160 cm. The condition of nearly normally incident, spilling (or mixed plunging-spilling) waves, breaking in a continuous way across the surf zone, prevailed during most of the experiments.

A. INSTRUMENTS

An extensive array of instruments was deployed to study nearshore wave dynamics. Measurements described here are from sensors located on an offshore transect from 10 m depth to across the surf zone (Fig. 1). The sensors were of three types: pressure (P), current (C) and surface-piercing-staff (W).

The pressure sensors were Stathem temperature-compensated transducers with dynamic range of either 912-2316 g/cm^2 or 912-3720 g/cm^2. They were statically precalibrated and postcalibrated by being lowered into a salt-water tank and were found quite linear; the gains differed by less than 2% between calibrations.

Current meters were two-axis, Marsh-McBirney electromagnetic, spherical (4 cm diameter) probes, with a three-pole output filter at 4 Hz. Precalibration and postcalibration of current meters showed little change in replicate runs with steady or oscillating velocity fields. The uncertainty associated with using a single gain factor for all frequencies is roughly estimated at ±5% in amplitudes (10% in variances).

The wave staffs were dual resistance wires with low noise, high resolution, and good electronic stability. The accuracy of the wave staffs was about ±3% based on repeatability of gain calibrations measured in the laboratory and *in situ*.

B. DATA ANALYSIS

Sea surface elevation and wave velocity components were retrieved from sensors by telemetering to shore and there recorded on a special receiver/tape recorder, described in detail by Lowe *et al.*, (1972). The sampling rate was 64 samples/s which was reduced to 2 samples/s by digital low-pass filtering. Record lengths of approximately 68 minutes from each data set were analyzed.

It was desired to examine only the sea-swell band of frequencies between 0.05 to 1.0 Hz (20 to 1 s periods). The data were first linearly detrended to exclude effects of the rising and falling tides. The data were then high pass filtered with a cut-off frequency of 0.05 Hz (20 s period). The high pass filter used a Fast Fourier Transform algorithm to obtain the amplitude spectrum of the entire 68 minute record. The Fourier coefficients corresponding to 0 to 0.05 Hz were used to synthesize a low frequency time series which was subtracted from the wave record. The limiting high frequency (Nyquist) was 1.0 Hz.

The energy density spectra were calculated in a similar manner for wave and velocity measurements using the Fast Fourier Transform (FFT) algorithm. A cosine-squared taper data window was applied to the time series to minimize leakage.

The highest maximum and lowest minimum of the surface elevation within a period interval defined, respectively, the crest and trough of a wave. A wave height $\underline{H}$ is defined as the total range of $\zeta(t)$ in that interval, the time between two consecutive zero-up-crossings of $\zeta(t)$ (see Fig. 2). Since the average wave period was about 14 sec, the total number of waves in the 68 min. record was about 300, which gives reasonable wave statistics. The height statistics of mean wave height $\overline{H}$, root mean square wave height H_{rms}, significant wave height $\overline{H}_{1/3}$ (average of the heights of the 1/3 highest waves), and $\overline{H}_{1/10}$ (average of the heights of the 1/10 highest waves), are calculated from the ordered set of wave heights.

The pdf and cumulative distributions of wave heights were calculated. The heights were normalized using the deep water root mean square value. Theoretical probability distributions were calculated using the Goda model and compared with measured distributions.

A deep water reference wave height was calculated by measuring the energy using current meter C9 located at about 4 m depth and backing the energy out to deep water. Kinetic energy spectra were calculated from the measured horizontal velocity spectra, $S_u(f)$ and $S_v(f)$; linear theory transfer functions were used to integrate the spectra over the water column, so that the average kinetic energy is

$$\langle KE(f) \rangle = |H_{KE}(f)|^2 [S_u(f) + S_v(f)] \tag{19}$$

where $|H_{KE}(f)|^2$ is the transfer function that relates the velocity spectrum components to the kinetic energy,

$$|H_{KE}(f)|^2 = \frac{1}{4k} \rho \frac{\sinh 2kh}{\cosh^2 k(h + z_m)} \tag{20}$$

where z_m is the measurement elevation. Guza and Thornton (1980) showed, for these same experiments, that using linear theory transfer functions to calculate average kinetic energy gave reasonable results. To first order in energy, the average potential energy equals the average kinetic energy. The potential energy in deep water is obtained by applying linear shoaling transformation

$$\langle PE(f) \rangle_{\text{deep water}} = |H_s(f)|^2 \langle PE(f) \rangle_{4m} , \quad (21)$$

where $H_s(f) = \sqrt{C_{g_o}/C_g}$, is the linear shoaling coefficient. The rms wave height is related to the PE and KE by

$$\langle PE \rangle = \frac{1}{8} \rho g H_{rms}^2 = \langle KE \rangle = \int_f \langle KE(f) \rangle df , \quad (22)$$

from which the deep water rms wave height, denoted henceforth by H_o, can be found.

To take advantage of the large number of current meters, current data were used to infer wave heights. The velocity signals were convolved using linear wave theory to obtain surface elevations. The complex Fourier spectra of the horizontal velocity components U(f), V(f) were first calculated and vectorially added. The complex surface elevation spectrum, X(f), was calculated applying the linear wave theory transfer function, H(f)

$$X(f) = \vec{H}(f) \cdot \vec{V}(f) \quad (23)$$

where

$$H(f) = \frac{\sinh kh}{\omega \cosh k(h + z_m)} \quad (24)$$

The complex surface elevation spectrum was then inverse transformed to obtain the surface elevation time series from which the wave height distribution is calculated. The entire 68 min. record was convolved at one time in order to minimize the end effects which result in spectral leakage.

IV. RESULTS

A. TYPICAL SPECTRA

A broad range of wave and weather conditions were encountered during the experiments. Typical velocity spectra for two days (Fig. 3, lower panel) include an example of very narrow band spectra calculated for November 20 for the current meters C22x and C23x which straddled the mean breaker line. In shallow water depths, the waves generally become more "peaky", resulting in increased energy at the harmonics. The presence of strong harmonics in the spectra indicates the importance of nonlinearities of the waves in shallow water. The spectral energy level decreases at all frequencies except at the very lowest from the deeper instrument C22x (heavy line) to the shallower instrument C23x due to breaking. The other typical spectra (Fig. 3, upper panel) are an example of combined sea and swell with a narrow band of energy at swell frequencies, but with broad band energy at higher frequencies.

B. HEIGHT STATISTICS

The wave height statistics for six days, inferred from wave staff and current meter data, are presented in Table II. The statistical parameters listed are: root-mean-square heights, H_{rms}, significant wave heights, $\bar{H}_{1/3}$, average of the heights of the 1/10 highest waves, $\bar{H}_{1/10}$, and the maximum height, H_{max}. These parameters were obtained from 68 min.

records. The reference wave height H_o, obtained by backing the energy measured at current meter C9 out to deep water, the frequency peak of the spectrum and the depth for each instrument, are also presented. Most of the wave staff measurements were made inside the surf zone, after the waves have started breaking.

Shoaling effects are observed in the data of Table II. The H_{rms}, $\bar{H}_{1/3}$, and $\bar{H}_{1/10}$, increase as depth decreases, until they reach the breaking point after which the wave heights decrease as the depth decreases, due to breaking.

The range of depths of the instruments is from about 570 cm to 40 cm. The average peak frequency (peak frequency) varied little during the experiments and was about 0.07 sec^{-1} (Table II). The relative depth for the waves at the peak frequency is $h/L < 1/25$ in all cases so that they can be considered shallow water waves.

C. COMPARISON OF EMPIRICAL WITH MODEL DISTRIBUTIONS

The Goda model is compared with measured data. The model is first run using Goda's original coefficients. This model results in over-prediction of the H_{rms}. The coefficients are changed to optimize the model's description of the wave height distribution qualitatively, and H_{rms} quantitatively. The H_{rms} parameter was calculated from the second moment of the wave height distribution and is, therefore, a more sensitive parameter to describe the shape of the distribution (particularly the tail) than, say, first moments such as the mean $\bar{H}$, $\bar{H}_{1/3}$, $\bar{H}_{1/10}$.

A comparison (Fig. 4) was made between the empirical wave height distribution normalized with the reference deep water wave height and Goda's model distribution for November 20. Starting in deep water, it is observed that the model fits quite well the empirical distribution obtained from the pressure sensor P7. It is clearly seen that the wave heights in deep water are essentially Rayleigh distributed. In shallow water the model over-predicts the tails and under-predicts the peaks. The smaller the depth the greater the errors (Figs. 4 and 5). Due to this over-prediction at the tails of the distribution the rms wave heights obtained by the model are larger than the measured ones.

To obtain a better agreement between the measured and the calculated rms wave heights, the higher limit of breaking and the range of breaking of the model are changed. Goda (1975) calculated the shoaling using the nonlinear theory of Shuto (1974) (see equations 10, 11 and 12). For all the ranges of wave heights, frequencies and depths used here, the values of gHT^2/h^2 are calculated and in all cases analyzed, fall in the third category, equation(12). This law was used to calculate the nonlinear shoaling coefficient K_s. Goda assumed a range of breaking between H1 and H2 that takes into account the variability of breaker heights and the use of a single frequency. The variable breaker height H_b is a function of the frequency, depth and bottom slope (see equation 18). The values of the coefficients used by Goda in his breaking criterion are the following: A1 = 0.18, A2 = 2/3 A1, K = 15 and p = 4/3, empirically assigned to give the best-fit with observed wave heights. The coefficients used here to give a qualitatively better fit with the measured distributions and quantitatively fit with H_{rms} are: A1 = 0.136, A2 = 1/2 A1, K = 20; p was left equal to the previous value. The most sensitive coefficient is A1 which was determined first. Values of A1 were calculated for various distributions by first obtaining the higher breaker limit (X1) from the measured empirical distributions as indicated by the maximum value of the distribution, and then calculating A1 using equation 18. The values of A1 were then averaged to give a single representative value for all distributions. The coefficient A2 was chosen as 1/2A1, which results in a more symmetrical distribution as indicated by the results. The coefficient K, which weights the slope of the beach, was determined by trial-and-error testing of Goda's model for a variety of values looking for the best fit of all the distributions. The model is not very sensitive to changes in K.

The comparison (Fig. 6) of the empirical distribution in deep water for November 20 with the distribution obtained applying the model used the new coefficients. In deep water, there is no notable difference from the original model's results (Fig. 4). In shallow water, the predicted values obtained with the modified model fit much better the empirical distributions than those obtained applying the original Goda model.

As stated earlier, the coefficients Goda originally specified were based on matching laboratory data for a two beach slopes of 1/10 and 1/50. The model was then applied to some field data, but unfortunately the beach geometry (slopes) were not given. The Torrey Pines Beach is approximately 1/50 at the beach face and the wave climate is characterized by long period (~14 sec) swell. The reason for differences in the model coefficients needed to fit this data set compared with Goda's suggested coefficients is not known.

D. COMPARISON OF RMS WAVE HEIGHTS

The model calculated H_{rms} values and measured values of H_{rms} calculated directly from the wave heights are used to test how well the model works. Table III shows the measured, Rayleigh, and the calculated Goda and modified Goda root-mean-square wave heights corresponding to the wave staffs and current meters for six different days.

Goda's model-predicted H_{rms} values are, in general, larger than the measured ones (Fig. 9). In an attempt to explain the differences, H_{rms} values obtained from the model were plotted against depth, deep water wave height and Ursell number; but no meaningful correlation was obtained with any of these variables.

Measured H_{rms} and calculated values assuming the wave heights are Rayleigh distributed so that $H_{rms} = \sqrt{8m_o}$ were compared (Fig. 8a). Measured and assumed Rayleigh significant wave heights were also compared (Fig. 8b). The comparisons show that the agreement between measured and Rayleigh statistics are good for both small and large wave heights, inside and outside the surf zone. The good comparisons with Rayleigh statistics suggests that the wave heights, although decreased by breaking, are still more nearly Rayleigh-distributed than cut-off Rayleigh, as suggested by Goda.

The change of the rms wave heights with depth, between the measured H_{rms} and the calculated ones obtained by the model first applying nonlinear (heavy line) and then linear shoaling (light line) were compared (Fig. 10). The model with nonlinear shoaling clearly over-predicts the values, while the model with linear shoaling gives reaonable values, compared with measurements. The nonlinear shoaling "blows up" in very shallow water (<30 cm) and should be ignored.

Measured and the calculated rms wave heights with depth obtained by applying linear and nonlinear shoaling using the modified coefficients were also compared (Fig. 10, lower panel). This figure illustrates that the modified Goda model fits better the data than the original does. The majority of the measured H_{rms} fall between the two curves obtained with nonlinear and linear shoaling. Based on the choice of coefficients, applying linear shoaling to Goda's model can give as good, or better, results as applying nonlinear shoaling.

The rms wave height values, obtained using the modified model coefficients, were plotted against depth, deep water wave height and Ursell number; no obvious correlation could be noted. It is found that the new predicted H_{rms} values compared with measured H_{rms} have an error of less than ±20% at all depths (with the exception of one anomalous point) (Fig. 11).

E. WAVE HEIGHT DISTRIBUTIONS USING CURRENT METERS

As described earlier, the surface elevations were derived by linearly convolving the velocity records and wave height distributions calculated. The basis for applying this analysis is the earlier work of Guza and Thornton (1980) where they showed, for this same data set, that linear theory spectral transformations could be used to calculate surface elevation standard deviations either from pressure meters or current meters with less than a 20% error, and typically less than 10%. Examples of the derived wave height distributions are considered for November 17 (Fig. 12). These measurements were made just outside the surf zone, at about the breaker point and inside the surf zone (current meters C23, C37 and C40 respectively). In general, the model overestimates the velocity derived wave height distributions more than the direct measurements. The reason for the discrepancy is that linear wave theory underestimates the surface elevations in convolving the velocities, particularly in the crest region of the waves. In other words, linear theory does not account for the finite amplitude of these highly nonlinear waves.

F. COMPARISON OF MODEL AND MEASURED CUMULATIVE DISTRIBUTIONS

The cumulative exceedance of wave height distributions normalized with rms deep water wave height were calculated applying the modified Goda model (using nonlinear shoaling) and plotted with the measured cumulative distribution for comparison. The cumulative exceedance distribution emphasizes information in the tail of the distribution. For an example in shallow water, inside the surf zone (116 cm depth), there is a good agreement between the measured and predicted distributions with a slight underprediction by the model in the tail (Fig. 13). With sensors located just outside the surf zone, under-prediction of the tail is larger and over-prediction in the middle range occurs (Fig. 14). In general, there is a better agreement between the two distributions well inside the surf zone, e.g., wave staffs W38 and W41, than those (W21 and W29) which were generally either at breaking or just outside the surf zone, the most nonlinear wave region.

V. CONCLUSIONS

It is confirmed that the wave heights in deeper water (7 m) are Rayleigh distributed.

Goda's model, using the empirical coefficients originally suggested on the basis of laboratory and poorly specified field measurements, over-predicts the tail of the distribution and under-predicts the peaks. As a consequence, the predicted rms wave heights are larger than the measured. As the depth decreases, the errors of the predicted distributions increase. To get a better fit with the measured wave height distributions, the coefficients in the breaking criterion used in Goda's model were modified. The values for Goda's breaking criterion giving the best fit to the measured data of this study are:

$$A1 = 0.136, \quad A2 = 1/2\ A1 \quad \text{and} \quad K = 20 .$$

The percentage of error between the measured and the predicted H_{rms} values from the model with these coefficients is les than ±20%.

Linear shoaling was found to be as good as nonlinear shoaling in applying Goda's model across the surf zone.

Good comparisons were obtained between empirical and Rayleigh-derived statistics. This indicates that the wave heights, although decreased by breaking, are still more Rayleigh-distributed than the cut-off Rayleigh-distributed as suggested by Goda.

Goda's model was tested here with a large amount of field data for a variety of wave conditions on a 1/50 beach slope. Further comparisons should be made for a variety of beach slopes and wave climates in order to test the general applicability of the model.

TABLE I. TRUNCATED PROBABILITY DENSITIES; THE DOTTED LINES REPRESENT THE ORIGINAL RAYLEIGH DISTRIBUTIONS AND THE HEAVY LINES REPRESENT THE MODIFIED DISTRIBUTIONS.

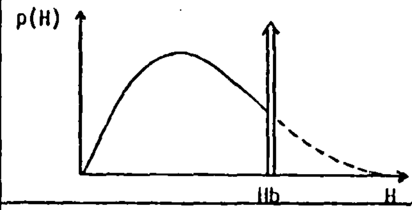
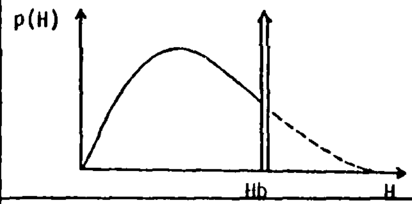
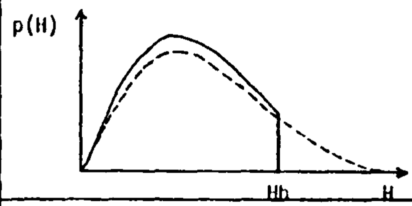
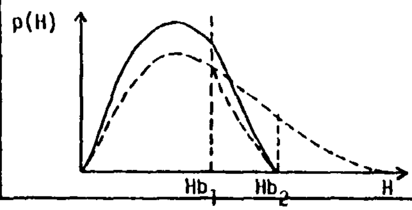
AUTHOR	DISTRIBUTION	SHOALING	BREAKFR CRITERIA
Collins (1970)		Linear	$\frac{Hb}{Ho} = 0.76\beta^{1/7}(Ho/Lo)^{-1/4}$ (After LeMehaute and Koh, 1967)
Battjes (1974)		Linear	$Hb = \frac{0.88}{k}\tanh(\frac{\gamma}{0.88}kh)$ (Modified after Miche, 1951)
Kuo and Kuo (1974)		Linear	$Hb = 0.63h$
Goda (1975)		Nonlinear (Shuto, 1974)	$\frac{Hb}{Ho} = A\frac{Lo}{Ho}(1-\exp(-1.5\frac{h}{Ho}\frac{Ho}{Lo}(1+K\tan^{P}\rho)))$ (After Goda, 1975)

TABLE II. WAVE HEIGHT STATISTICS
(all values in cm)

Date	Inst	h	H_o	f	H_{rms}	$H_{1/3}$	$H_{1/10}$	H_{max}
Nov 4	W41	82	42.5	.0703	33.2	44.4	53.2	74.3
	W38	125	42.5	.0703	44.8	61.5	73.4	98.1
	W21	177	42.5	.0703	50.6	71.8	90.9	131.3
	W29	225	42.5	.0703	56.7	81.3	113.8	188.3
Nov 10	W21	170	66.1	.0632	61.0	85.5	107.4	140.4
Nov 17	W41	92	44.8	.0729	37.8	50.7	59.4	79.5
	W38	141	44.8	.0729	52.0	72.1	86.9	111.5
	W21	197	44.8	.0729	54.1	76.2	94.1	139.2
	W29	209	44.8	.0729	52.0	72.8	93.7	154.0
Nov 20	W38	116	52.4	.0666	35.9	49.3	57.9	83.8
	W21	153	52.4	.0666	48.6	68.1	84.2	120.3
	W29	182	52.4	.0666	73.1	110.2	143.0	202.7
Nov 20	C42	39	52.4	.0703	18.0	27.0	33.8	49.1
	C39	102	52.4	.0703	35.6	50.5	59.8	82.6
	C37	116	52.4	.0703	36.5	53.6	62.1	81.8
	C36	142	52.4	.0703	40.1	60.4	69.8	89.5
	C23	147	52.4	.0703	51.6	80.2	98.0	118.9
	C22	188	52.4	.0703	60.8	96.1	127.7	159.3
	C19	250	52.4	.0703	68.9	105.1	149.0	210.4
	C15	355	52.4	.0703	58.7	88.5	125.5	217.9
	C09	571	52.4	.0703	55.8	84.0	115.2	192.4
Nov 24	W38	65	36.4	.0639	10.1	14.5	18.4	26.3
	W21	86	36.4	.0715	26.7	36.6	43.5	55.8
Nov 18	W41	84	55.4	.0757	33.8	45.8	55.4	109.1
	W21	195	55.4	.1552	61.4	87.2	103.9	131.7
	W29	198	55.4	.0756	63.9	91.3	117.2	166.3

TABLE III. MEASURED AND CALCULATED RMS WAVE HEIGHTS OBTAINED WITH GODA'S MODEL AND MODIFIED GODA'S MODEL (all values in cm)

		RMS WAVE HEIGHTS				SIG. HEIGHTS	
Date	Inst.	Meas.	Ray.	Goda	Mdf.G.	Meas.	Ray
Nov 4	W41	33.2	33.7	34.6	30.9	44.4	46.9
	W38	44.8	46.2	55.9	47.5	61.5	63.4
	W21	50.6	52.3	67.3	51.1	71.8	71.6
	W29	56.7	58.2	65.3	58.5	81.3	80.2
Nov 10	W21	61.0	64.9	85.3	64.5	85.5	86.3
Nov 17	W41	37.8	37.9	48.6	34.7	50.7	53.5
	W38	52.0	52.2	66.1	53.4	72.1	73.5
	W21	54.1	55.6	70.3	56.0	76.2	76.5
	W29	52.0	53.8	69.8	58.1	72.8	73.5
Nov 20	W38	35.9	36.2	50.3	43.9	49.3	50.8
	W21	48.6	50.3	68.3	44.9	68.1	68.7
	W29	73.1	67.5	77.6	53.3	110.2	103.4
Nov 20	C42	18.0	18.2	21.4	18.0	27.0	25.4
	C39	35.6	36.1	54.0	38.5	50.5	50.3
	C37	36.5	36.3	60.3	43.9	53.6	51.6
	C36	40.1	40.0	70.1	53.8	60.4	56.7
	C23	51.6	50.0	71.5	55.7	80.2	73.0
	C22	60.8	57.5	79.1	54.9	96.1	86.0
	C19	68.9	65.0	78.3	67.5	105.1	97.4
	C15	58.7	60.9	72.0	64.0	88.5	83.0
	C09	55.8	60.7	64.0	55.6	84.0	79.0
Nov 24	W38	10.1	10.7	26.7	24.4	14.5	14.3
	W21	26.7	27.5	44.6	32.7	36.6	37.8
Nov 18	W41	33.8	35.5	33.4	31.4	45.8	47.8
	W21	61.4	59.7	59.6	50.8	87.2	86.8
	W29	63.9	61.7	80.7	57.5	91.3	90.4

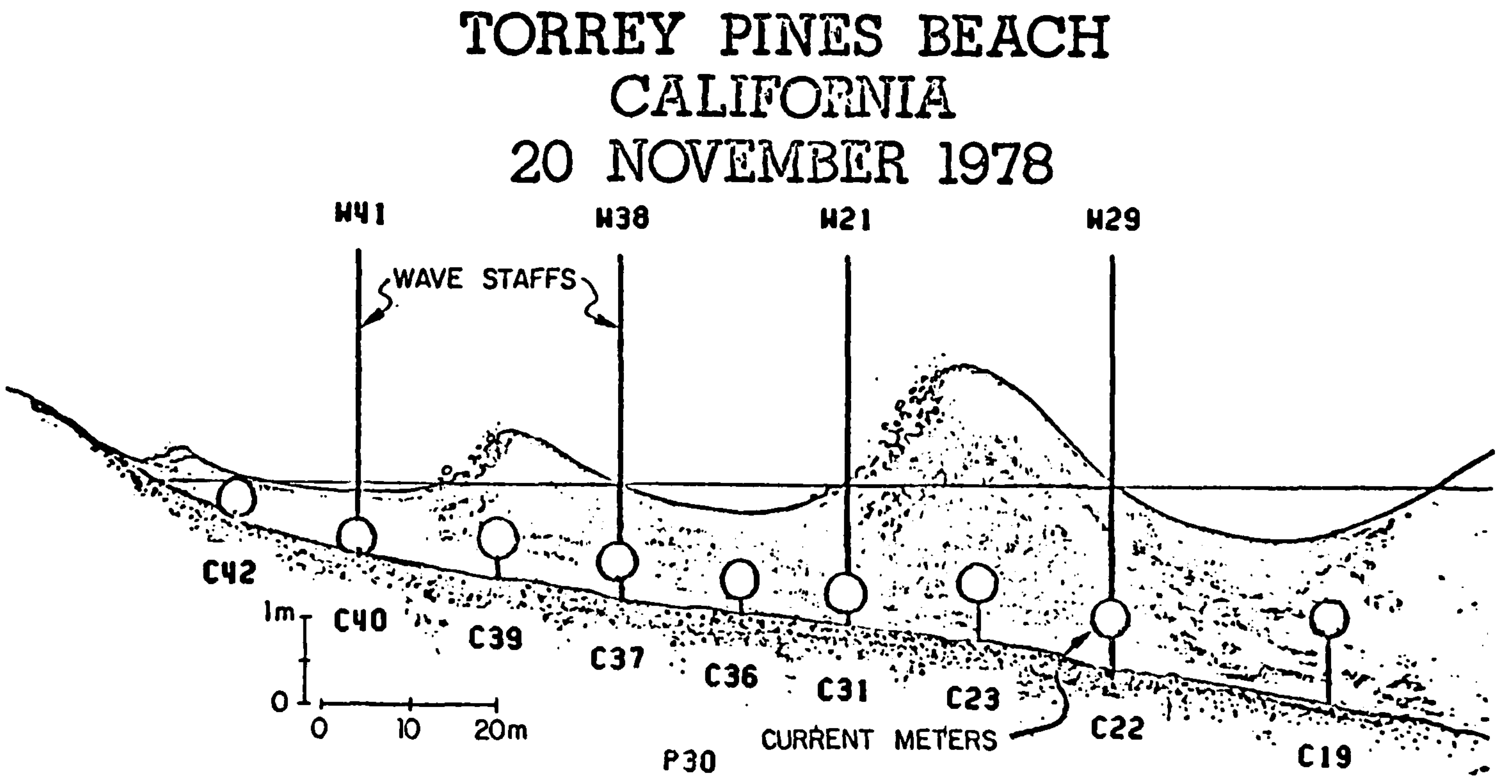
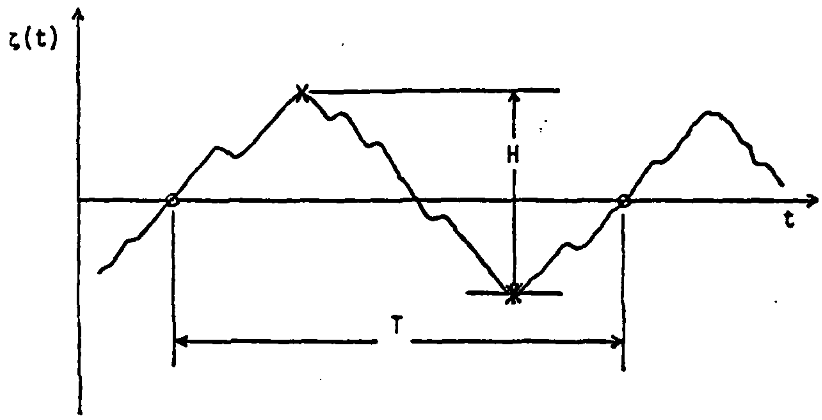


Figure 1. Cross-section of surf zone showing instrument spacing and elevations relative to measured waves on 20 November 1978 at Torrey Pines Beach, California.



where X is a crest
* is a trough
O is the zero-up crossing

Figure 2. Definition sketch of zero-up-crossing wave heights.

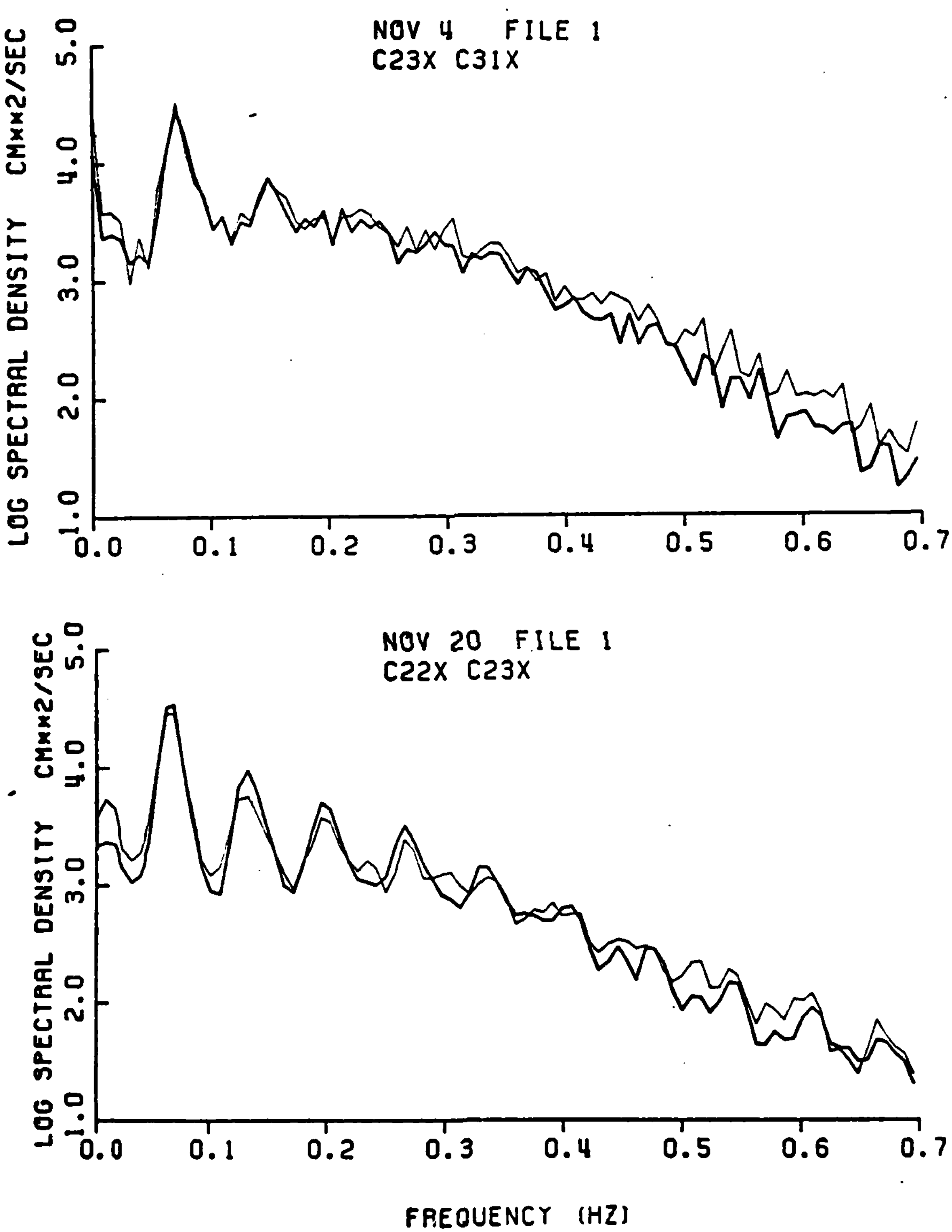


Figure 3. Typical spectra measured during the experiments.

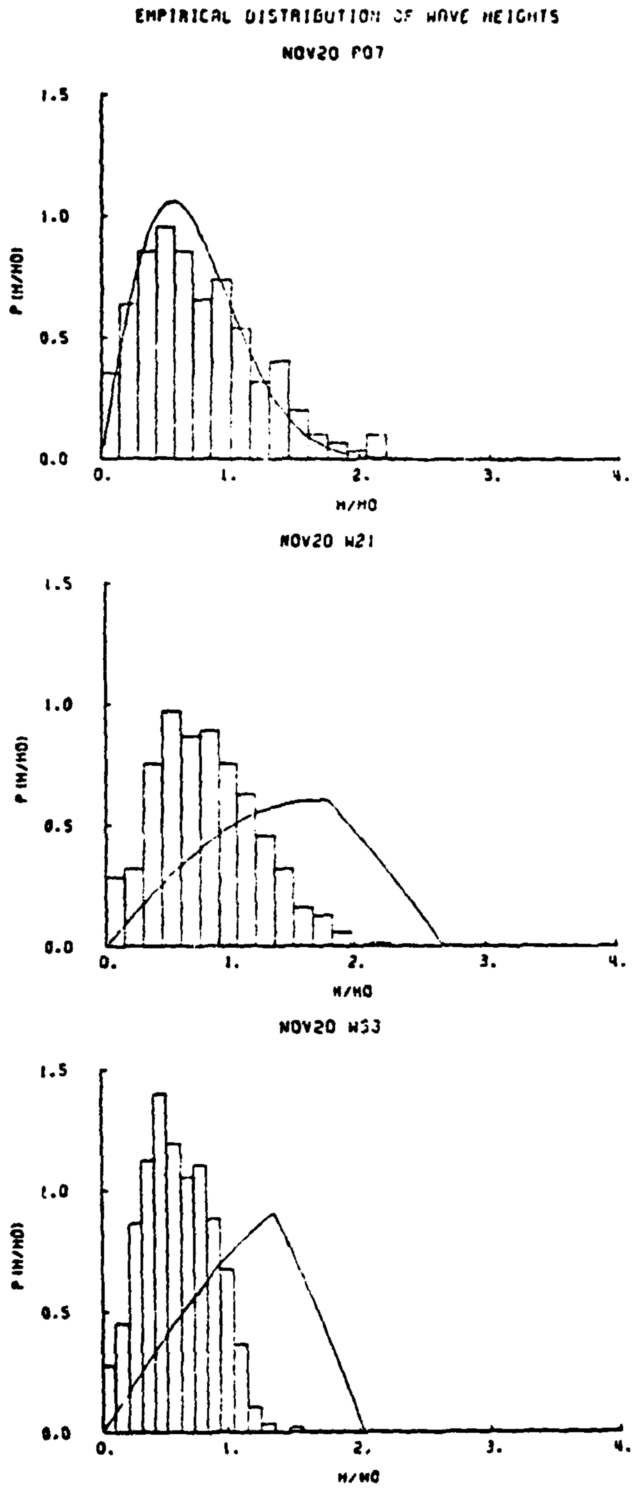


Figure 4. Empirical distribution of wave heights compared with those predicted with Goda's model, starting in deep water (P7) and going into shallow water (W21, W38), 20 November 1978.

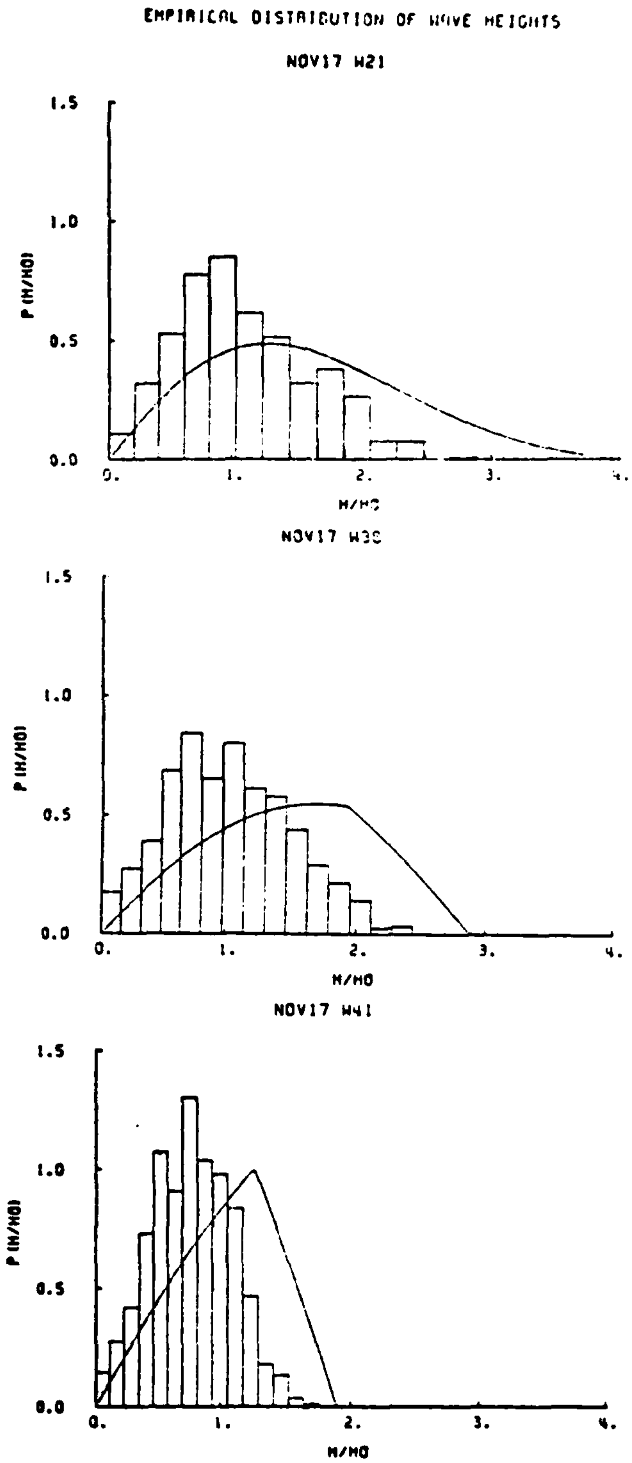


Figure 5. Empirical distribution of wave heights compared with those predicted with Goda's model, starting in deep water (W21) and going into shallow water (W38, W41), 17 November 1978.

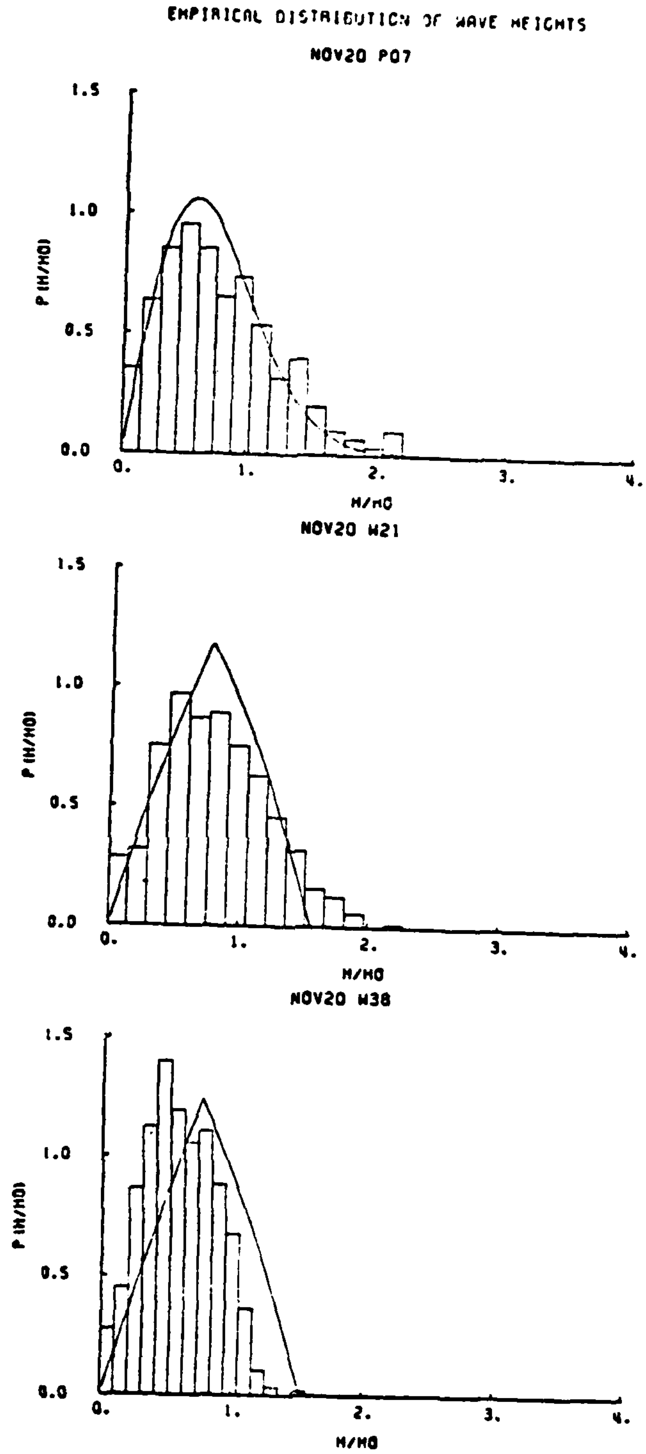


Figure 6. Empirical distribution of wave heights compared with those predicted with the modified Goda's model, 20 November 1978.

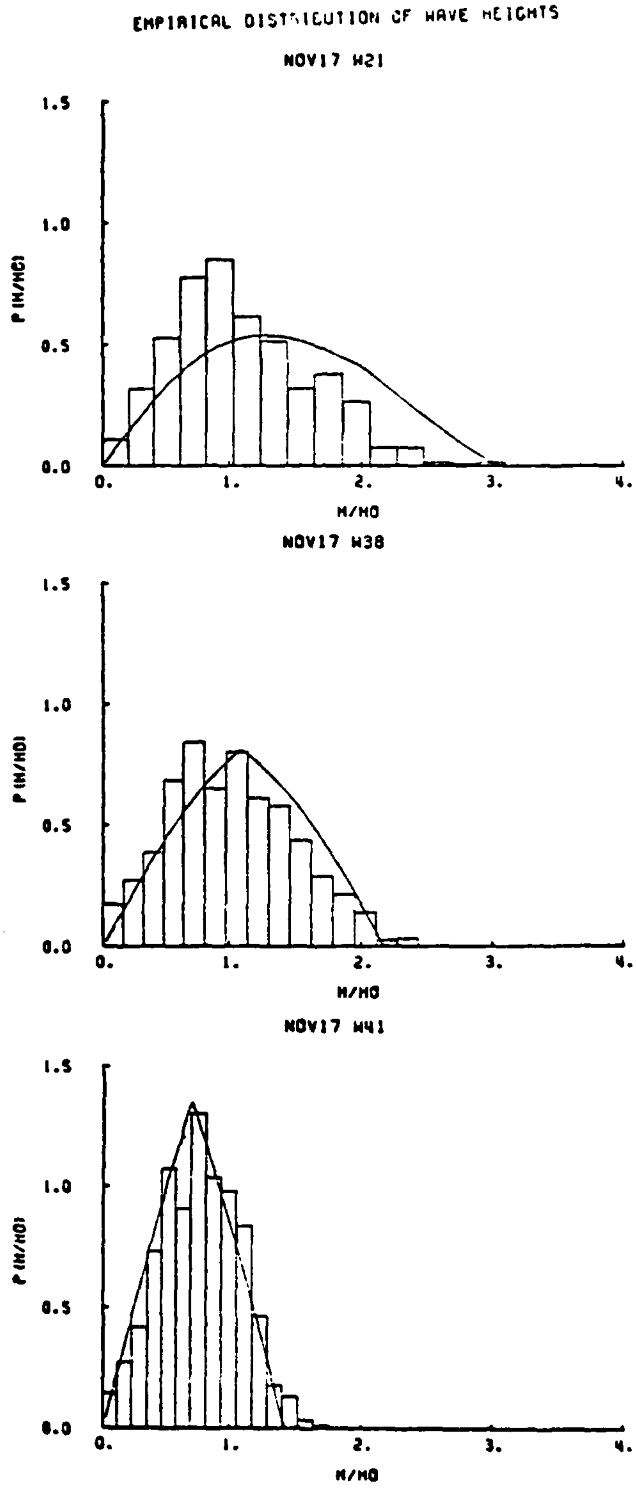


Figure 7. Empirical distribution of wave heights compared with those predicted with the modified Goda's model, 17 November 1978.

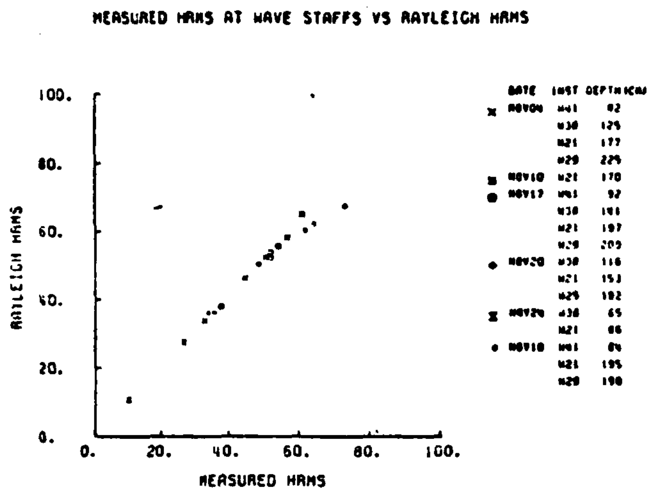


Figure 8a. Range of measured and Rayleigh root-mean-square wave heights.

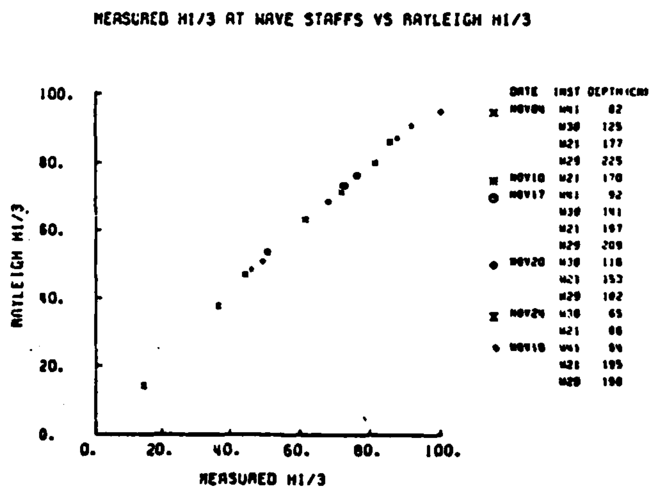


Figure 8b. Range of measured and Rayleigh significant wave heights.

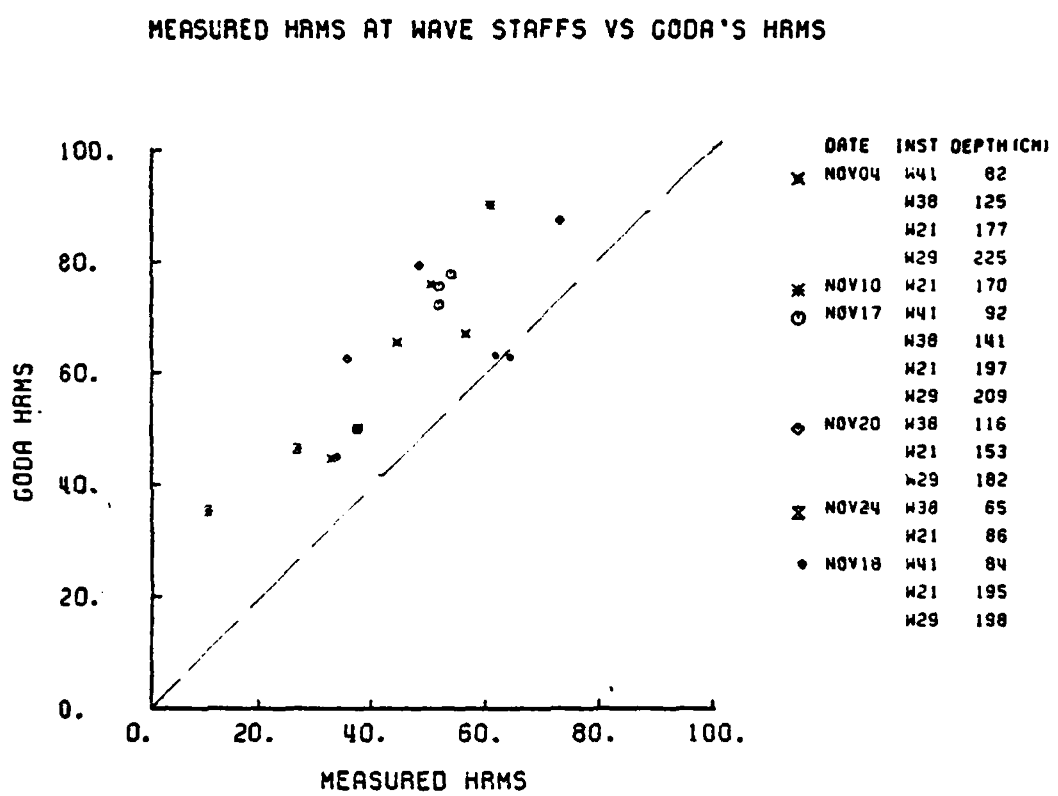


Figure 9. Correlation of measured rms wave heights with calculated Goda's rms wave heights.

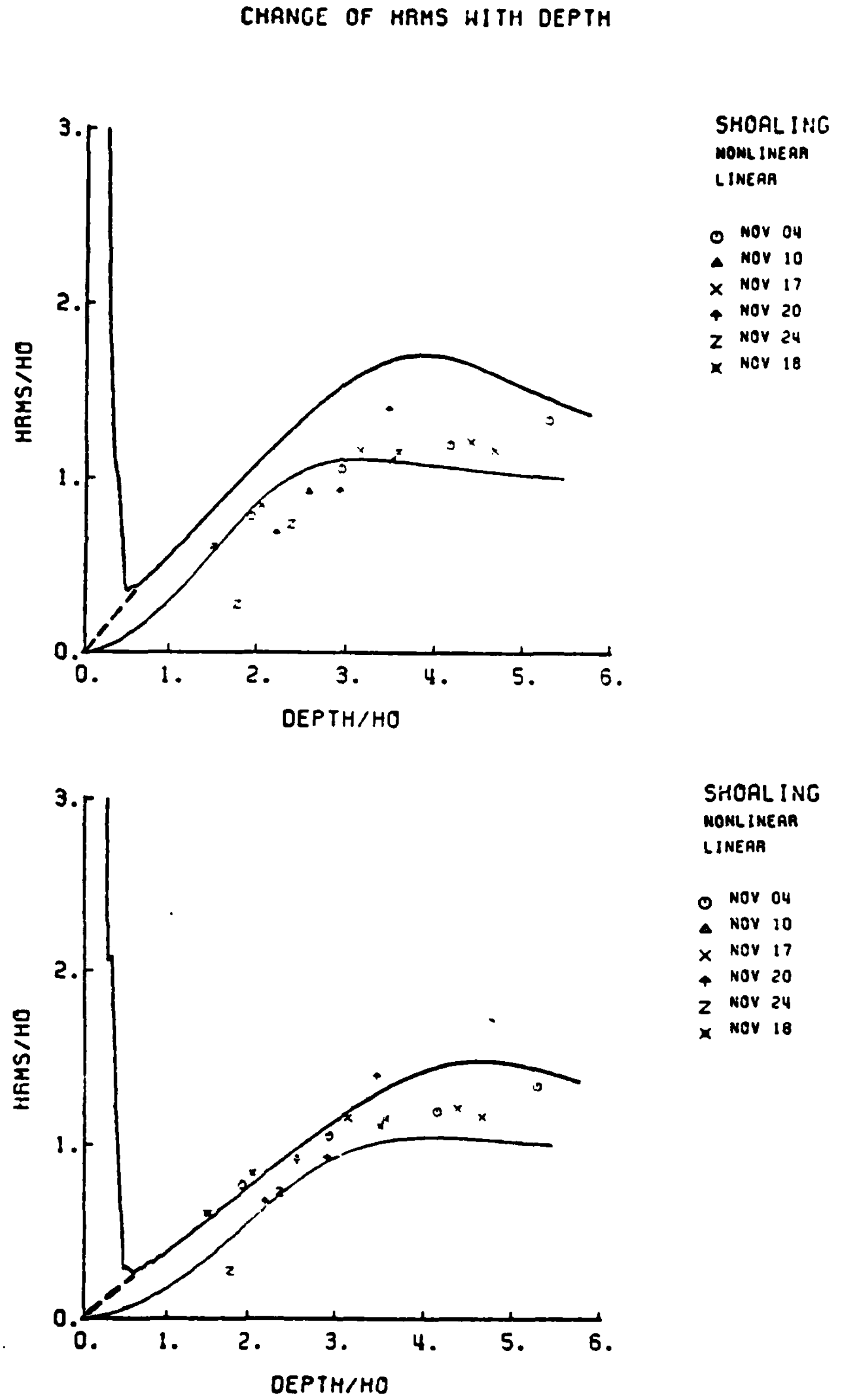


Figure 10. Comparison of the changes of H_{rms} with the Goda's model applying nonlinear (heavy line) and linear shoaling (light line). Upper figure illustrates Goda's original model; lower figure illustrates the use of the modified coefficients in applying Goda's model.

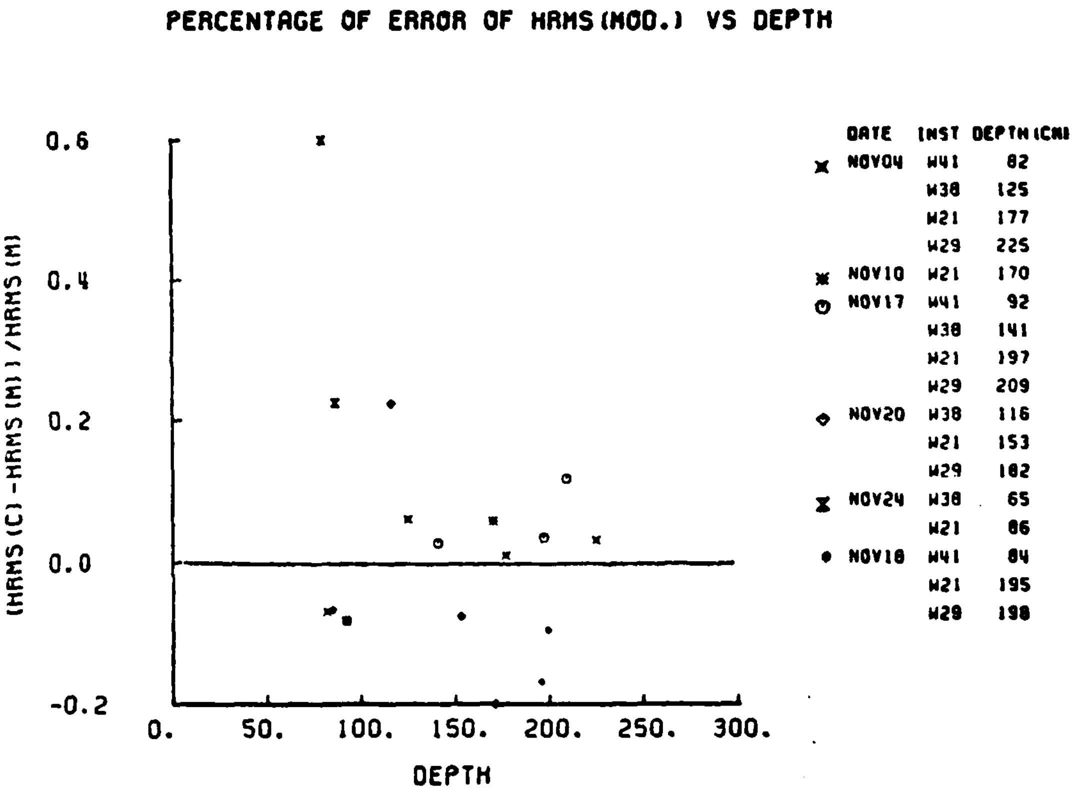


Figure 11. Percentage error of predicted (modified model) compared with measured rms wave heights.

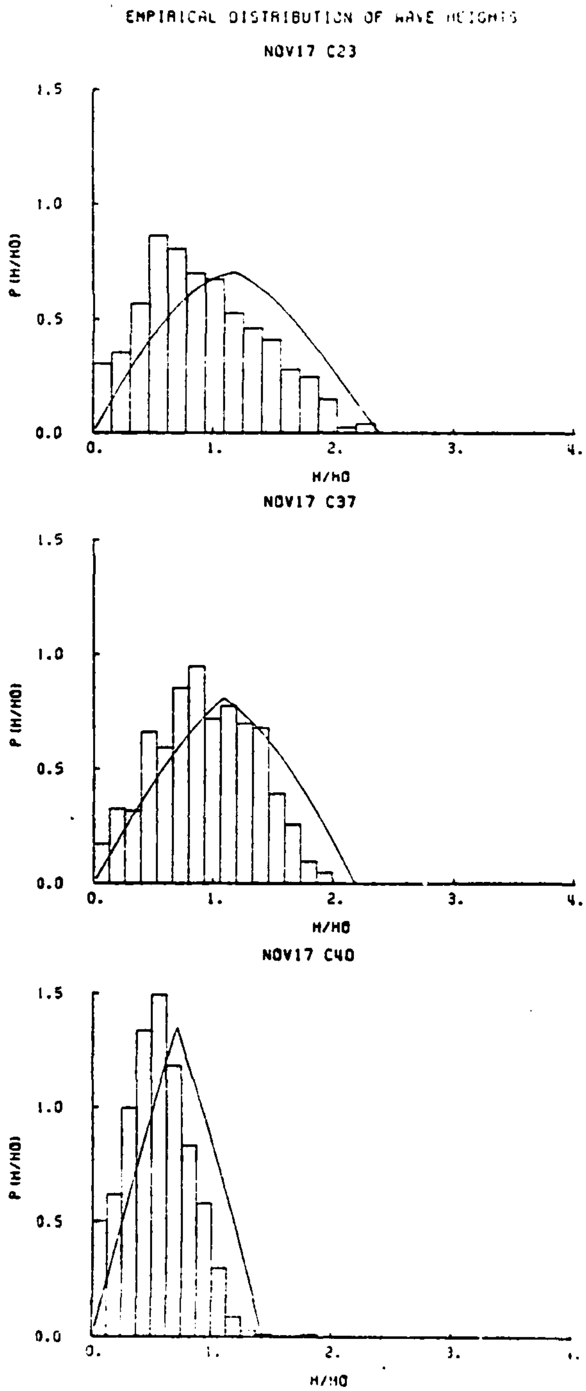
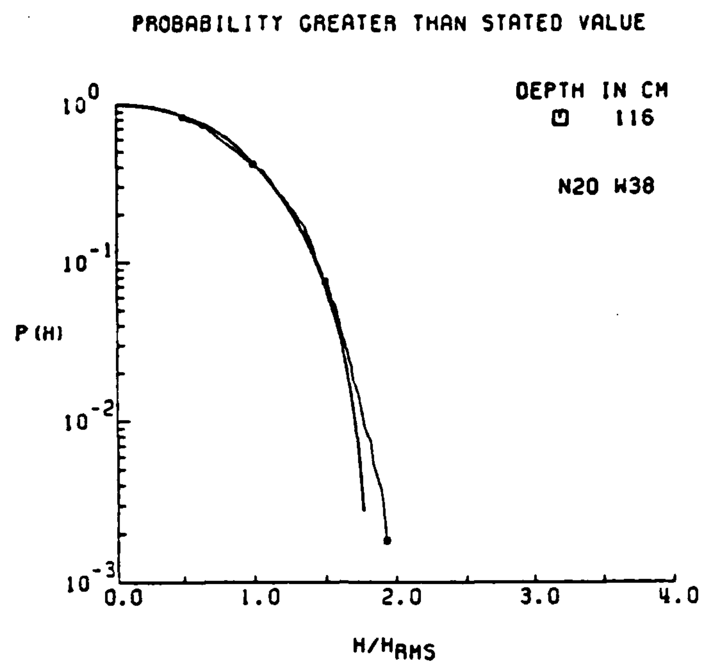


Figure 12. Empirical distributions of wave heights obtained from current meters (C23, C37 and C40) compared with predicted wave heights calculated with the modified model, 17 November 1978.



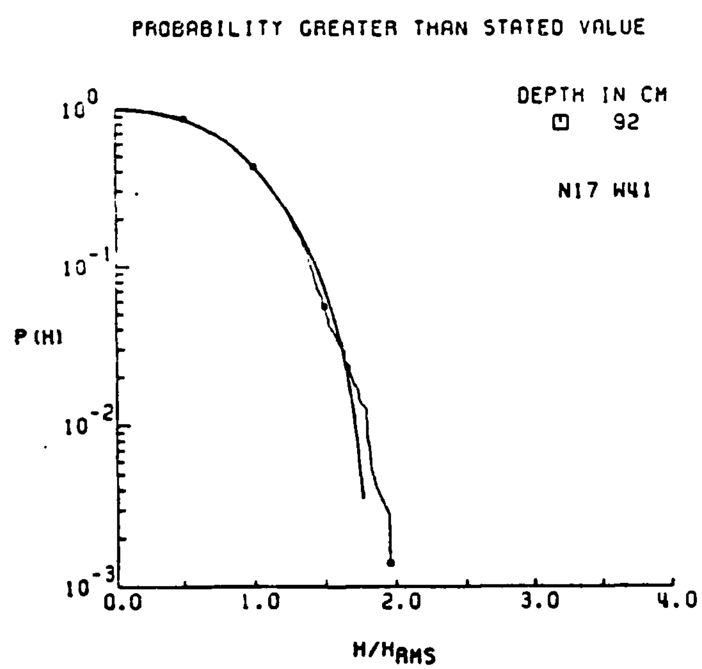


Figure 13. Comparison of measured cumulative exceedance distributions with predicted distributions (modified model), 20 November (W38) and 17 November 1978 (W41).

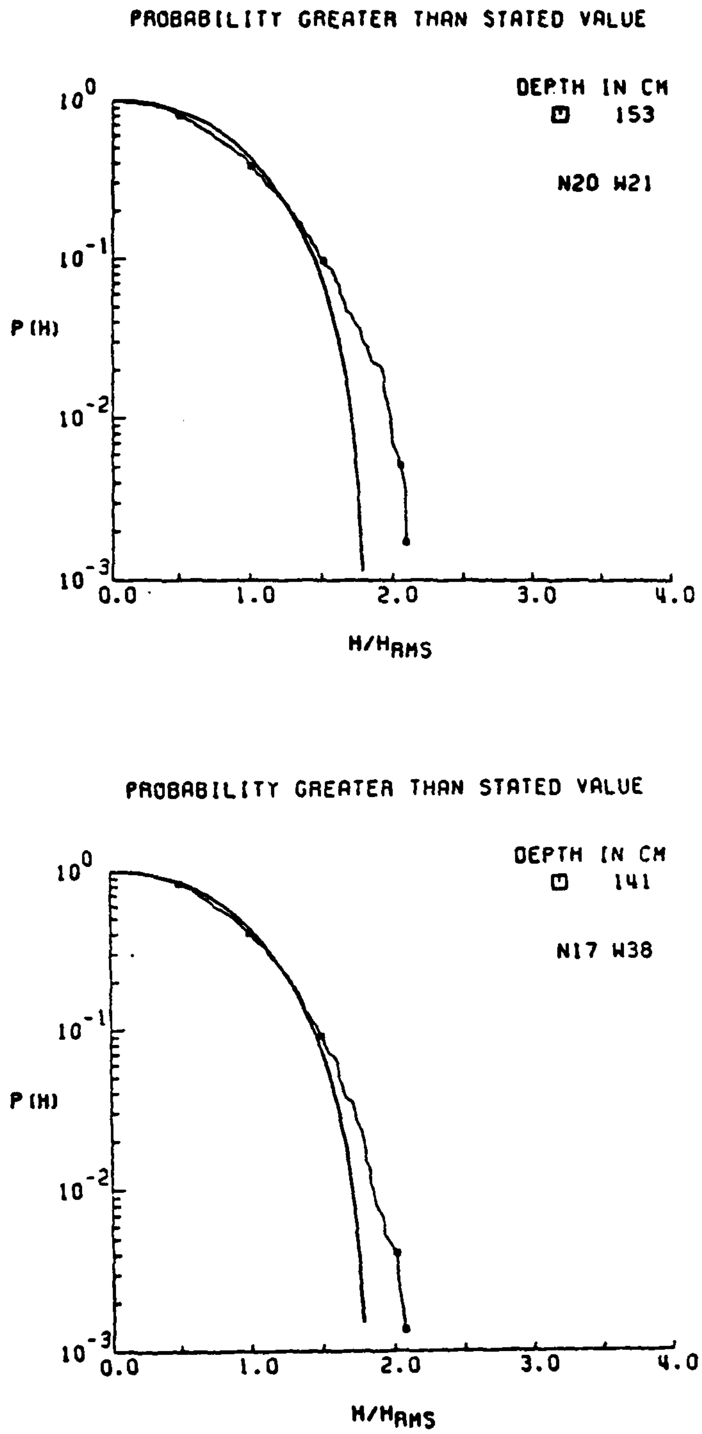


Figure 14. Comparison of measured cumulative exceedance distributions with predicted distributions (modified model), 20 November (W21) and 17 November 1978 (W38).

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